

A HIGH-PERFORMANCE MEMS TRANSFORMER FOR SILICON RF ICs

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ABSTRACT

A new spiral-type suspended transformer for silicon radio frequency integrated circuits (RF ICs) has been fabricated by surface micromachining technology. The fabricated transformer on standard silicon substrate has shown a low insertion loss of 1.9dB at 1GHz by reducing substrate coupling and ohmic loss using the proposed MEMS technology. Equivalent circuit models for the spiral-type suspended transformer have been extracted and shown that they agree well with measured characteristics.

INTRODUCTION

In order to satisfy the demand for low-cost monolithic RF IC's, researches have been intensively carried out for integration of passive components on RF IC's. This is because RF passive components (e.g. inductors, transformers) available from conventional silicon IC technologies have poor performance due to substrate loss from relatively high conductivity in silicon substrate and the ohmic loss from thin metallization [1]. Recently, transformers have been required in many RF IC applications for impedance matching/transforming, signal coupling, phase splitting (balun), etc [2-5]. However, on-chip transformers acquired free from the conventional silicon IC technologies do not meet the requirement from circuit designers. In order to address this issue, non-standard substrates such as high-resistivity silicon or insulating substrates [3], or sometimes with insulation layers [2], have been used to reduce substrate loss. Also, special processes of thick Al or Cu metallization have been used to reduce ohmic loss.

In this paper, we have achieved significant improvement on transformer performance by employing the metal surface micromachining process previously

reported by our group [7]. This process provides an air-gap to the micromachined transformers to significantly reduce the substrate coupling loss and also utilizes thick metal layers ($>10\mu\text{m}$) to reduce ohmic loss. We have also achieved a high magnetic coupling factor (<0.81) in the fabricated spiral-type transformers.

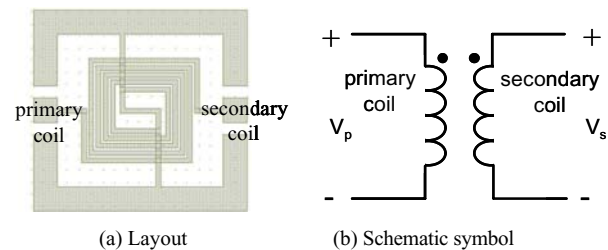


Figure 1. Integrated transformer

INTEGRATED TRANSFORMER DESIGN

Transformer as shown in Fig. 1 must transfer the a.c. signal from the primary coil to the secondary coil without significant loss. Insertion loss, which is the most important figure of merit in integrated transformers, represents how efficiently a signal in the primary coil is transmitted to the secondary coil. The insertion loss is determined by metal ohmic loss, substrate dissipation, and magnetic coupling factor [2-3],[6],[8].

The metal ohmic loss in transformer can be reduced by thick metal and/or low resistivity metal. Substrate dissipation can be suppressed by high resistivity substrate or thick insulating layers for isolation between transformer and silicon substrate.

The magnetic coupling factor, k , is calculated by following equation:

$$k = \frac{L_m}{\sqrt{L_p \cdot L_s}} \quad (1)$$

removed as well (Fig. 2(f)).

This proposed technology, SMM, can be easily adopted in the conventional CMOS RF IC's as post-IC processes because it can be processed at low temperature ($< 120^{\circ}\text{C}$).

Fig. 3 shows the SEM picture of the fabricated transformers. These transformers are non-inverting types [1] and have a 1:1 turn ratio. The transformer in Fig.3 (a) is type 1 transformer in Table I and that in Fig. 3(b) is type 2.

EXPERIMENTAL RESULTS

Table I shows the dimensions of the fabricated transformers. The definitions of pitch and inner diameter in Table I are shown in Fig. 3(a). S-parameters of the fabricated transformers have been measured in a frequency range from 0.05 to 10GHz by HP8720 network analyzer. Pad parasitic effects are extracted from the measurement by de-embedding open pads.

Table I. Dimension of fabricated transformer

	Number of turn	Line width	Pitch	Inner Diameter
Type 1	4.5	30 μm	50 μm	200 μm
Type 2	2.5	30 μm	40 μm	200 μm
Type 3	2.5	30 μm	50 μm	200 μm

Fig. 4 shows the measured and modeled characteristics of the type 1 transformer in the frequency range from 0.05 to 10GHz, presenting the minimum insertion loss (S21) of 1.9dB at 1GHz. The S21 in Fig. 4 has a sharp null around 7GHz. This results from coupling capacitance between the primary and secondary coils [2],[10].

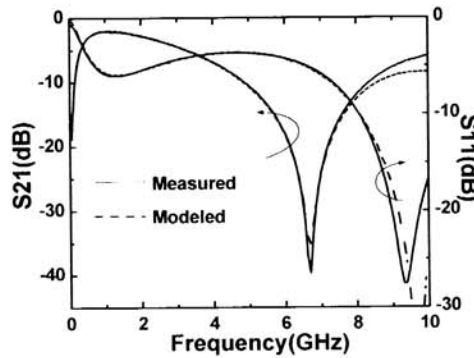


Figure 4. Measured and modeled S-parameters of the Type 1 transformer

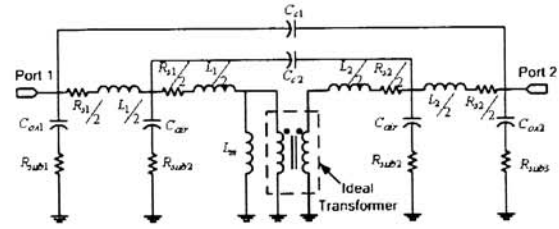


Figure 5. Equivalent circuit for the fabricated transformer

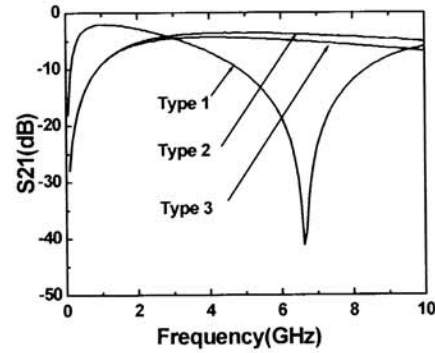


Figure 6. Measured S21 of the fabricated transformers

Fig. 5 is the equivalent circuit model of fabricated transformers. L_1 and L_2 are leakage inductance of the primary and secondary coils, respectively. L_m represents the mutual inductance between the two coils. R_{s1} and R_{s2} are series resistance of each coil, respectively. C_{c1} and C_{c2} model the coupling capacitance between the primary and secondary coils. Substrate parasitic effects are modeled by C_{ox1} , C_{ox2} , C_{airs} , R_{sub1} , R_{sub2} , and R_{sub3} . Parameter values in Table II are extracted from the measured data by using HP-EEsof Libra.

As can be seen in Fig. 4, the proposed equivalent circuit model fits the measured data very well. Fig. 6 shows the measured S21 parameters of type 1, 2, 3 transformers. The minimum insertion loss of type 2 transformer is 3.5dB at 5.2GHz and that of type 3 is 4.3dB at 3.8GHz. The coupling factors of type 1, 2, and 3 transformers are measured as 0.81, 0.69, and 0.63, respectively. The values are calculated by equation (1) and (2) from the extracted parameter values in Table II.

The minimum insertion loss of type 1 transformer is the lowest among other type because the number of turns of type 1 is large. Also, the insertion loss of type 2 is lower than that of type 3 because type 2 has shorter pitch than type 3. Table III compares the performance of the various RF integrated transformers fabricated on the

where,

$$L_p = L_1 + L_m, \quad L_s = L_2 + L_m \quad (2)$$

L_m is the mutual inductance. L_p and L_s are primary and secondary coil inductances, respectively. L_1 and L_2 are the leakage inductance. In order to get a large coupling factor, leakage inductance must be minimized. This means that magnetic leakage flux between primary and secondary turns must be reduced. In practical transformer implementation, increasing the number of turns in transformers and decreasing the space between metal lines are good methods to achieve a high coupling factor [6].

FABRICATION

Spiral-type suspended transformers have been fabricated by using sacrificial metallic mold (SMM) method [7]. The SMM method employs thick photoresist (PR) molding and copper electroplating. Typical conventional methods to form multi-metal structures use a PR or polymer mold and electroplating [9].

These methods require to deposit several seed layers for multi-metal structures; therefore, the PR or polymer

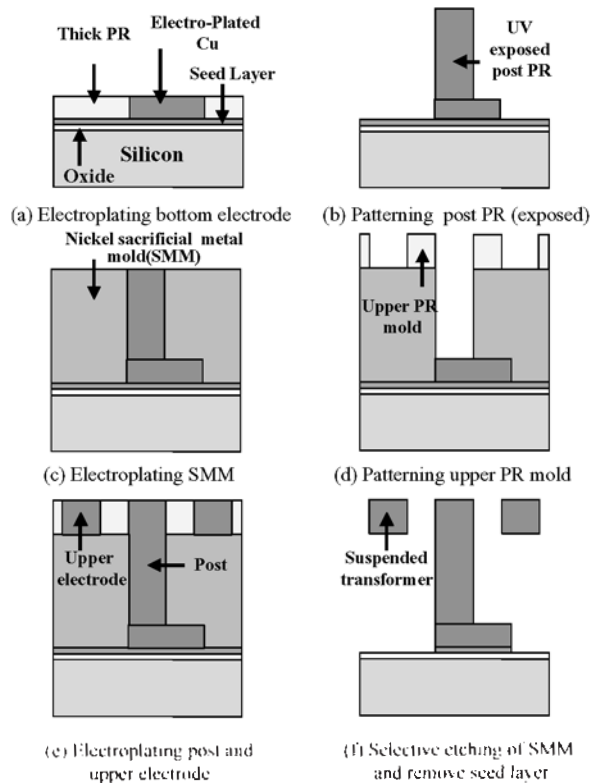
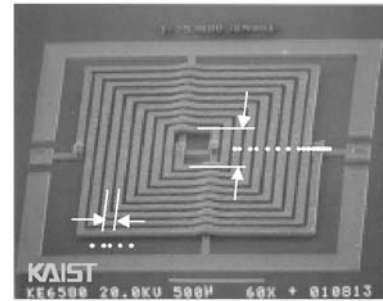
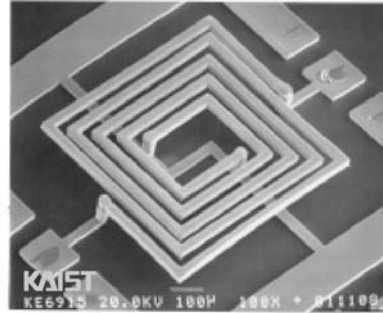


Figure 2. Cross-sectional view of the fabrication process



(a) Type 1 transformer



(b) Type 2 transformer

Figure 3. SEM photograph of fabricated transformers.

molds for electroplating can be easily deformed due to thermal stability problem. On the contrary, the SMM method can easily produce not only a few tens micron mold for electroplating but also robust metal lines of a few tens of microns in thickness, utilizing the same single seed layer at the bottom. This is because SMM method uses a metal mold instead of the PR/polymer mold; therefore, only one seed layer is required at the bottom and thermal stability problem of the mold is diminished.

Figure 2 shows the fabrication process flow for suspended MEMS transformers. First, seed metal layer is deposited on a standard silicon wafer with a resistivity of $10\Omega\cdot\text{cm}$, where a $1\mu\text{m}$ -thick silicon dioxide layer is grown for isolation between the seed layer and silicon substrate. Bottom copper electrodes are formed by thick photoresist (PR) lithography followed by electroplating (Fig. 2(a)). The post area is defined by the thick PR mold in Fig. 2(b), and the remaining area is covered by the sacrificial metal mold (SMM) made of electroplated Ni (Fig. 2(c)). During the second PR mold is patterned for upper electrodes, the post PR mold is also developed away (Fig. 2(d)). The posts and the upper electrodes are simultaneously formed by the second copper electroplating (Fig. 2(e)). Finally, the PR mold and Ni SMM are removed selectively, and the seed layer is

Table II. Extracted equivalent circuit model parameters of fabricated transformers

	L_1 (nH)	L_2 (nH)	L_m (nH)	R_{s1} (Ω)	R_{s2} (Ω)	C_{c1} (fF)	C_{c2} (fF)	C_{ox1} (fF)	C_{ox2} (fF)	C_{air} (fF)	R_{sub1} (Ω)	R_{sub2} (Ω)	R_{sub3} (Ω)
Type 1	2.36	2.37	9.8	1.64	1.63	33	202	110	109	168	513	579	87
Type 2	0.76	0.74	1.67	0.92	1.04	2.38	35.5	57.5	57.6	115.4	534	586.5	3977
Type 3	0.99	0.96	1.64	0.96	1.07	2.9	20.1	13.1	10.7	93.3	527	534	3268

Table III. Performance comparison of the various RF integrated transformers fabricated on silicon substrate

Ref	Type	minimum insertion loss (dB)	Dielectric material (thickness)	Metal for transformer (thickness)	Substrate ,resistivity
[2]	Spiral	3.22dB at 1.4GHz	SiO ₂ (6 μ m)	2 μ m with $\rho=0.03\Omega$ -cm	Si $\rho=15\Omega$ -cm
[3]	Spiral	5dB at 1GHz	polyimide and Si ₃ N ₄ ($>8\mu$ m)	Al (2.5 μ m)	Si, $\rho=2k\Omega$ -cm
[6]	Solenoid	7dB at 7GHz	SiO ₂ (3 μ m)	Al-Cu (2.7 μ m)	Si, $\rho=N.A.$
Type1	Spiral	1.9dB at 1GHz	SiO ₂ (1 μ m) + air (25 μ m)	Cu (20 μ m)	$\rho=10\Omega$ -cm

silicon substrates. The type 1 transformer reported in this work shows the best performance in terms of insertion loss among all the transformers fabricated on silicon substrate.

CONCLUSIONS

Suspended spiral-type transformers for RF silicon ICs have been designed and fabricated by using surface micromachining technology. The proposed fabrication method allows to build thick metal lines for reducing ohmic loss and sufficient air gap between the transformer and silicon substrate for suppressing the substrate coupling. The fabricated transformers show the minimum insertion loss of 1.9dB at 1GHz on the standard silicon substrate. This technology can allow monolithic integration of high-performance transformers on silicon RF ICs as post IC processes at low temperature below 120°C.

ACKNOWLEDGEMENTS

This work has been supported by National Research Laboratory program from Ministry of Science and Technology in Korea. The authors would like to thank B.-G. Kim and S.-I. Chang for taking SEM pictures, and Prof. S.-C. Hong for supporting HP-EEsof Libra.

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